

Charm Lifetimes and Mixing

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Abstract. A review of the latest results on charm lifetimes and D -mixing is presented. The e^+e^- collider experiments are now able to measure charm lifetimes quite precisely, however comparisons with the latest results from fixed-target experiments show that possible systematic effects could be evident. The new D -mixing results from the B -factories have changed the picture that is emerging. Although the new world averaged value of y_{CP} is now consistent with zero, there is still a very interesting and favoured scenario if the strong phase difference between the Doubly-Cabibbo-suppressed and the Cabibbo-flavoured $D^0 \rightarrow K\pi$ decay is large.

MOTIVATION FOR THE STUDY OF CHARM LIFETIMES

The study of charm lifetimes is essentially a study of strong interactions [1], and in particular provide a test of the theoretically challenged part of the Standard Model, namely non-perturbative QCD. It is hoped that experimental results in charm lifetimes (possibly combined with other charm results), can give some guidance as to what is needed to theoretically describe strong interactions at all energy scales. This is important not only to improve our theoretical understanding of strong interactions, but also because the theoretical tools used to calculate lifetimes are the same or similar to those used in other areas, for example to extract V_{cs} and V_{cd} in charm decays; to calculate the b -particle lifetimes; and to extract other Standard Model parameters or decay constants in heavy flavor physics.

The other motivation is more mundane. Theoretical calculations are used to calculate decay rates whereas experimentally one measures branching fractions. One needs precise particle lifetimes to convert measured branching ratios to decay rates so one can compare to theory and to extract Standard Model parameters. Lifetimes are also important as an experimental tool since the correctness of the measured lifetime will test techniques or probe systematic effects in other areas where lifetimes and lifetime resolution is important. For example in D and B_s Δm mixing measurements or in $\Delta\Gamma$ measurements for D and B mesons.

¹ Talk presented at the 9th International Symposium on Heavy Flavors, California Institute of Technology, Pasadena, Sept. 10-13, 2001.

TABLE 1. Comparison of experiments with recent results on charm lifetimes and mixing

	Fixed Target			e^+e^- Collider		
Experiment	E791	SELEX	FOCUS	CLEO	BaBar	BELLE
Beam	hadronic		photon	off-resonance e^+e^-		
Charm	$\sim 10^5$	$\sim 10^4$	$\sim 10^6$	$> 10^6$		
σ_t (fs)	~ 40	~ 20	~ 40	~ 140	~ 160	
Method	Uses vertex detachment cut			Needs average IP position		
	Uses 3-D decay length			Uses \sim 2-D decay length		

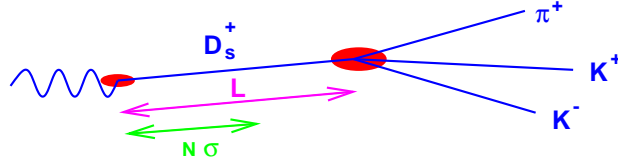


FIGURE 1. Illustration of decay length L and vertex separation

COMPARISON OF EXPERIMENTS

Table 1 shows a comparison of the experiments for which new results in charm lifetimes and mixing have been presented recently. These include both fixed-target experiments and experiments at e^+e^- colliders. This is significant as the two types of experiments are quite different and will thus have different systematics. Therefore a comparison of the results between the two types of experiments will be an important check of any systematic effects.

Typically fixed-target experiments have excellent vertex and proper time resolutions in 3-dimensions but large (non-charm) backgrounds. These backgrounds are eliminated by selecting decay vertices that are well separated from the production vertex, *e.g.* $L > N\sigma_L$ (see Fig.1), and optionally also outside of target material. This means that short-lived decays are preferentially eliminated and the proper time distribution would look like that given in Fig.2(a) requiring large non-uniform acceptance corrections as illustrated in Fig.2(b). This problem is avoided by using the reduced proper time, $t' = (L - N\sigma_L)/\beta\gamma c$, which starts the clock at the minimum allowed proper time. The lifetime follows the same exponential wherever one chooses to start, so the reduced proper time distribution will follow an exponential with the true lifetime. This is illustrated in Figures 1(c) and (d). The acceptance correction obtained using Monte Carlo simulations can be checked with data by using K_S^0 decays reconstructed with the vertex detector as these have a well measured lifetime. Absorption corrections are typically small and can similarly be checked in data.

In fixed-target experiments there is usually a compromise between systematics due to backgrounds and systematics due to the acceptance correction. The latter can become larger if one uses other types of vertexing cuts to eliminate more background at the expense of introducing a (larger) lifetime dependence in the acceptance.

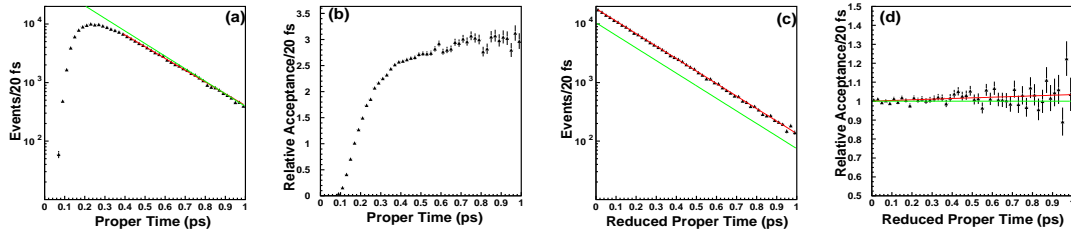


FIGURE 2. (a) Proper time distribution for a MC sample when a vertex separation requirement is made to reduce backgrounds; (b) resulting acceptance correction function; (c) reduced proper time distribution showing an exponential where the offset line shows the slope of the true generated lifetime; (d) acceptance as a function of reduced proper time.

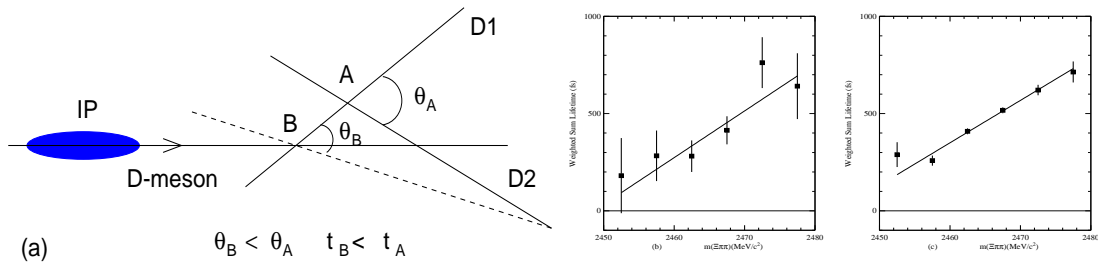


FIGURE 3. (a) Illustration of altering a track slope so that track $D2$ is at intersection point B instead of the unbiased initial reconstruction point A ; (b) Correlation between mass and lifetime as seen by CLEO in data; and (c) in MC.

In contrast, the e^+e^- experiments operating near B threshold have much less background but have poorer vertex resolutions and hence poorer proper time resolutions. The average interaction point is normally used for constraining the location of the production point but its position is usually only known well in 2-dimensions or even only 1-dimension. The proper time resolution can be large compared to the charm particle lifetime under study. Due to proper time smearing from the poor resolution one has to take into account this smearing on an event-by-event basis. This necessarily requires a more complicated event-by-event likelihood analysis where one has to parameterize the time and mass resolutions as well as background lifetime distributions. These resolutions can be known well as they can be obtained from data but they are not usually parameterizable by a simple function. The resolution can sometimes be improved by using additional constraints like forcing the reconstructed decay secondaries to come from a single point or using the average IP position. However this can also lead to fit biases and subsequent corrections. An example of this is illustrated in Fig.3(a) where constraining a decay track to come from point B instead of A will decrease the opening angle and hence also the reconstructed mass, it would also decrease the lifetime. This produces a correlation between the reconstructed mass and lifetime as seen in CLEO for $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ decays in both data, Fig.3(b), and MC Fig.3(c) [2]. Systematic concerns are therefore usually related to the fit method, resolutions and fit biases.

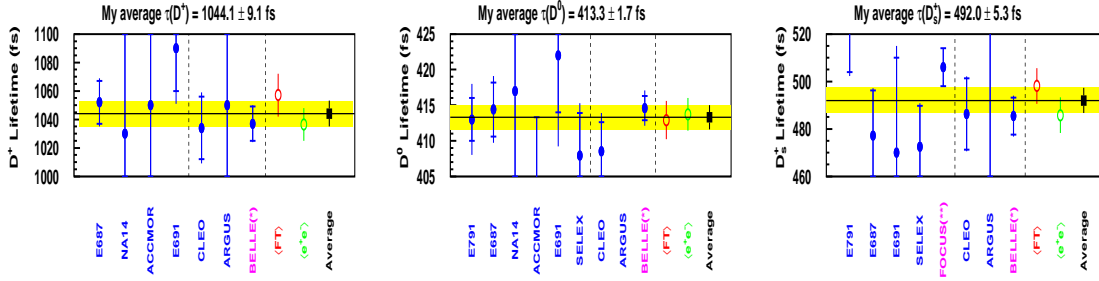


FIGURE 4. Summaries of recent D -meson lifetime measurements and their averages.

TABLE 2. World averaged lifetimes including also preliminary results.

Quantity	World Average	Quantity	World Average
$\tau(D^+)$ (fs)	1044.1 ± 9.1	$\tau(\Lambda_c^+)$ (fs)	200.2 ± 3.2
$\tau(D^0)$ (fs)	413.3 ± 1.7	$\tau(\Xi_c^+)$ (fs)	433 ± 19
$\tau(D_s^+)$ (fs)	492.0 ± 5.3	$\tau(\Xi_c^0)$ (fs)	106.0^{+9}_{-8}

RESULTS ON LIFETIMES

Both BaBar and BELLE would like to demonstrate that they have excellent understanding of their vertexing and lifetime resolutions by measuring the lifetimes of the charm particles. In fact they already have enough data to get charm lifetimes with a precision comparable to the current world averages. BELLE has led the way with preliminary lifetime measurements for the D^0 , D^+ and D_s^+ mesons [3]. A summary of the most recent charm lifetime results are given in Fig.4. Together with the published results [4, 5, 6] I have included the preliminary results shown in the figure in my new world averages given in Table 2. For the D_s^+ FOCUS preliminary result [7] which does not yet include a systematic uncertainty I have taken the total uncertainty to be $\sqrt{2}$ times the statistical error. The fixed-target and e^+e^- averages are also separately shown and agree fairly well suggesting no additional unaccounted-for systematics. The e^+e^- averages are currently dominated by the preliminary BELLE measurements.

The ratio $\tau(D_s^+)/\tau(D^0)$ continues to be of interest in determining the importance of the suppression of W-exchange and W-annihilation contributions in D -meson decays. There are now three direct measurements of this ratio giving an average of 1.171 ± 0.018 which agrees well with just taking the ratio of the two world average lifetimes: 1.190 ± 0.014 . The ratio is much larger than 1.07 which is the maximum expected size for no W-exchange/W-annihilation contributions [8]. An accurately measured value for this ratio can be used to determine phenomenologically the relative size of W-exchange/W-annihilation contributions [9].

There are new preliminary FOCUS lifetime results for the Λ_c^+ , Ξ_c^+ and Ξ_c^0 baryons [10, 11] and a CLEO preliminary lifetime result for Ξ_c^+ [2]. These are shown together with published results in Fig.5. As previously, for the preliminary FOCUS lifetime result for Ξ_c^0 which does not include a systematic uncertainty I have taken the total uncertainty

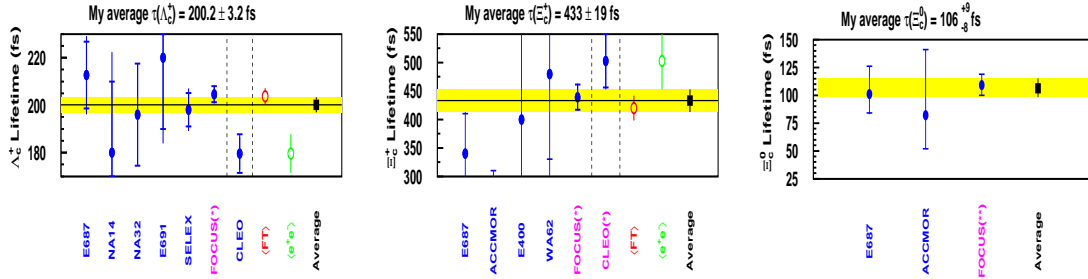


FIGURE 5. Summaries of recent charm baryon lifetime measurements and their averages.

to be $\sqrt{2}$ times the statistical error in determining the world average.

There are two items of note in the new results. The first is that the CLEO published lifetime for Λ_c^+ appears to disagree with the fixed-target average value when the new FOCUS preliminary number is included. This could point to a systematic problem starting to appear which might be related to the short-lived nature of the Λ_c^+ decay. An example of a possible effect is the mass-lifetime correlation seen in CLEO which introduces very large MC correlations to the lifetime. It is known that the size and type of the resonance sub-structure of a decay like $\Lambda_c^+ \rightarrow pK^-\pi^+$ can be important to the acceptance corrections, and may also be important in the mass-lifetime correlations since the resonance sub-structure alters the angular distributions of the daughter tracks. Uncertainties related to the resonance sub-structure can thus introduce additional systematic studies. Any systematic problems between the fixed-target and e^+e^- results should be kept in mind as the BaBar and BELLE lifetime and mixing results become more precise.

The other interesting feature of the new results is that the ratio $\tau(\Xi_c^+)/\tau(\Lambda_c^+)$ is now 2.16 ± 0.11 compared to the PDG2000 value of $1.60^{+0.31}_{-0.22}$. Many of the calculations favour a value of 1.2–1.6 though with large uncertainties [12]. It would be interesting to see if one can feed back into the calculations this new information and others like the $\tau(D_s^+)/\tau(D^0)$ ratio to get a better understanding, and to see if it affects the prediction for other related quantities like the ratio $\tau(\Lambda_b^0)/\tau(B^0)$. Both the mentioned results suggest that the W-exchange contribution is much more important than have so far been assumed in the calculations.

D-MIXING REVIEW

The parameters we use to describe D-mixing can best be defined by the relevant equations relating the states with definite mass and lifetimes: $|D_H(t)\rangle = e^{-im_H t} e^{-\Gamma_H t/2} |D_H\rangle$, and $|D_L(t)\rangle = e^{-im_L t} e^{-\Gamma_L t/2} |D_L\rangle$ to the observed $|D^0\rangle$ and $|\overline{D}^0\rangle$ states: $|D_H\rangle = p|D^0\rangle + q|\overline{D}^0\rangle$ and $|D_L\rangle = p|D^0\rangle - q|\overline{D}^0\rangle$. So for example the doubly-Cabibbo-suppressed (DCS) decay rate $\Gamma(D^0 \rightarrow K^+\pi^-) = |\langle K^+\pi^- | T | D^0(t) \rangle|^2$. We will assume CP conservation in charm decays and use the following approximations for charm: $|q/p| = 1$ and $|x|, |y|, R_{DCS} \ll 1$. Where $x = \Delta m/\Gamma$, $\Delta m = m_H - m_L$, $\Gamma = (\Gamma_H + \Gamma_L)/2$, $y = \Delta\Gamma/2\Gamma = (\Gamma_{C\text{Peven}} - \Gamma_{C\text{Podd}})/(\Gamma_{C\text{Peven}} + \Gamma_{C\text{Podd}}) = y_{CP}$, and

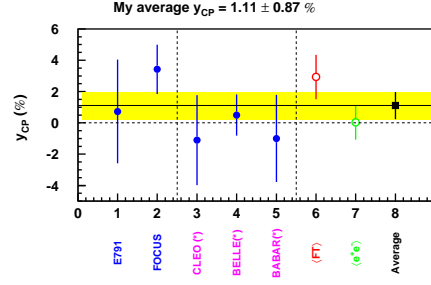


FIGURE 6. Summary of recent y_{CP} measurements.

$R_{DCS} = |\langle K^+\pi^- | T | D^0 \rangle / \langle K^+\pi^- | T | \bar{D}^0 \rangle|^2$. The ratio of the “wrong-sign” $D^0 \rightarrow K^+\pi^-$ to “right-sign” $D^0 \rightarrow K^-\pi^+$ decays is given by

$$R_{WS}(t) = \left[R_{DCS} + (y \cos \delta - x \sin \delta) t \sqrt{R_{DCS}} + \frac{(x^2 + y^2)}{4} t^2 \right] e^{-t}$$

$$R_{WS}(t) = \left[R_{DCS} + y' t \sqrt{R_{DCS}} + \frac{(x'^2 + y'^2)}{4} t^2 \right] e^{-t}$$

where $y' \equiv y \cos \delta - x \sin \delta$ and $x' \equiv x \cos \delta + y \sin \delta$ and δ is the strong phase difference between the Cabibbo-favoured and the DCS decay.

Information on the charm mixing parameters can be obtained in several ways:

1. Measure the lifetime difference between CP-even, CP-odd and flavour specific states to give y_{CP} .
2. Measure wrong-sign semileptonic decays which do not require good lifetime resolution but only give information on $(x^2 + y^2)$ and cannot separate x and y .
3. Measure wrong-sign hadronic decays like $D^0 \rightarrow K^+\pi^-$ which require a lifetime study and high S/B and can give information on both x^2 and y separately. However there is an additional complication of an unknown strong phase difference, e.g. $\delta_{K\pi}$ between $D^0 \rightarrow K^+\pi^-$ and $D^0 \rightarrow K^-\pi^+$ contributions.

The published results are summarized in Fig.7(a) which include the y_{CP} measurement from FOCUS [15], the limits on (x', y') from CLEO allowing and not allowing for CP violation [14], and the E791 limits from semileptonic decays [13].

The preliminary measurements from CLEO [16], BELLE [3] and BaBar [17] for y_{CP} are given in Fig.6. Including these produces a world average of $1.11 \pm 0.87\%$ which is quite consistent with zero². However the situation is still interesting due to in part to a preliminary result from FOCUS for the allowed region in x' and y' [19]. The 95% confidence level allowed regions for the FOCUS and CLEO measurements are given in Fig.7(b) in the (x, y) space assuming the strong phase difference $\delta_{K\pi} = 0$. The slightly

² At “press time” the y_{CP} value of $+0.5 \pm 1.0^{+0.8}_{-0.9}$ shown by BELLE at the conference was superseded by a new value of $-0.5 \pm 1.0^{+0.7}_{-0.8}$ contained in their new preprint [18]. The same data sample was used but the analysis contained updated MC corrections. This moves the world average value down to 0.63 ± 0.85 .

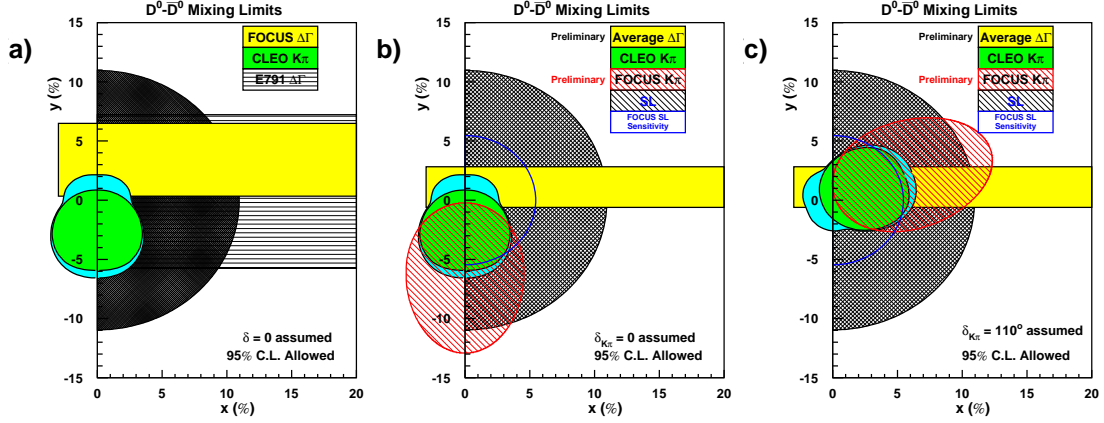


FIGURE 7. Summary of D-mixing results showing 95% confidence level allowed regions in (x,y) (a) for published results assuming $\delta_{K\pi} = 0$; and including preliminary results assuming (b) $\delta_{K\pi} = 0$ and (c) $\delta_{K\pi} = 110^\circ$.

larger (lighter) region for CLEO is when CP-conservation is not assumed. Also shown are the allowed region in y from the combined lifetime difference measurements assuming no CP-violation, and the circular allowed region from wrong-sign semileptonic decay limits from E791 [13]. The smaller circular line gives the expected size of the allowed region from FOCUS wrong-sign semileptonic decays [20].

Even though I do not have the likelihood contour of the CLEO allowed region in order to combine the FOCUS and CLEO results, it can be seen that the combined allowed region is beginning to exclude zero, especially if no CP-violation is assumed. The other point is that the combined FOCUS and CLEO $K\pi$ result for the allowed region does not agree well with the world average allowed y_{CP} range when one assumes $\delta_{K\pi} = 0$. This could indicate one of three things: it is just a statistical fluctuation; the systematic uncertainties are underestimated; or the most interesting is that $\delta_{K\pi}$ is large and non-zero. Knowing the value of $\delta_{K\pi}$ is crucially important. For example in the absence of a theoretically favoured value, the experimentally preferred value is about 110° as shown in Fig.7(c). This would be a really interesting situation since the favoured scenario is with y near zero and a large value of x of $\approx 3\%$ ³. This is the most likely expected signature of new physics beyond the Standard Model since these can produce sizable non-zero values in Δm but not usually in $\Delta\Gamma$.

CONCLUSIONS

Charm lifetime measurements continue to be an interesting way to study non-perturbative strong interaction physics and evaluate possible systematic problems

³ Note that the new lower world average value of y_{CP} does not significantly change these favoured values.

for measurements that require good lifetime resolutions. The larger than expected values of $\tau(D_s^+)/\tau(D^0)$ and $\tau(\Xi_c^+)/\tau(\Lambda_c^+)$ indicates that W-exchange is much more important than normally thought which could have implications on other theoretical predictions, like $\tau(\Lambda_b^+)/\tau(B^0)$.

The D-mixing situation is still very interesting as the data now favour a y value near zero and a large value of x of $\approx 3\%$. This could be a signature of new physics beyond the Standard Model. However it requires the strong phase difference $\delta_{K\pi} \approx 110^\circ$ which is unexpected theoretically. The possibility that this is a statistical fluctuation or a systematic underestimation can be greatly clarified by new precise D-mixing results from BaBar and BELLE and we look forward eagerly for these results in the future.

ACKNOWLEDGMENTS

I wish to thank Monika Grothe and Jun'ichi Tanaka for providing the BaBar and BELLE results respectively, and for providing prompt replies to my questions.

REFERENCES

1. G. Bellini, I. I. Y. Bigi and P. J. Dornan, *Phys. Rept.*, **289**, 1 (1997).
2. M. Artuso *et al.*, "Measurement of the Ξ_c^+ Lifetime", CLEO-CONF-01-03, Jul. (2001) hep-ex/0107040.
3. J. Tanaka, *these proceedings*; and K. Abe *et al.*, "Precise Measurements of Charm Meson Lifetimes and the Search for $D^0 - \bar{D}^0$ Mixing at Belle", BELLE-CONF-0131 (2001).
4. D. E. Groom *et al.*, *Eur. Phys. Jour.*, **C15**, 1 (2000); and partial update for edition 2002.
5. A. Kushnirenko, *et al.*, *Phys. Rev. Lett.* **85**, 5243–5246 (2001).
6. M. Iori *et al.*, "Measurement of the D_s^\pm Lifetime", FERMILAB-PUB-01-086-E, May (2001) hep-ex/0106005.
7. H. W. K. Cheung, FOCUS collaboration, "Preliminary D_s^+ Lifetime from FOCUS", presented at the APS Centennial Meeting, Atlanta, Georgia, U.S.A., March 20-26 1999.
8. I. I. Bigi and N. G. Uraltsev, *Z. Physik.*, **C62**, 623 (1994).
9. Harry W. K. Cheung, "Review of Charm Lifetimes", FERMILAB-CONF-99-344, Jul. (1999) hep-ex/9912021. In proceedings of the 8th International Symposium on Heavy Flavour Physics, Southampton, U.K., 25-29 July 1999, PRHEP-hf8/022.
10. E. W. Vaandering, FOCUS collaboration, "FOCUS Spectroscopy and Lifetimes", presented at the 9th Intern. Conf. on Hadron Spectroscopy, Protvino, Russia, Aug. 25–Sep. 1 (2001) http://www.hep.vanderbilt.edu/~vondo/focus-public/hadron_2001.ps
11. J. M. Link *et al.*, "A New Measurement of the Ξ_c^+ Lifetime", Submitted to *Phys. Lett. B*, FERMILAB-PUB-01-296-E, Oct. (2001) hep-ex/0107040.
12. B. Guberina, R. Ruckl and J. Trampetic, *Z. Phys.* **C33** 297 (1986); M. A. Shifman and M. B. Voloshin, *Sov. Phys. JETP* **64**, 698 (1986); B. Blok and M. A. Shifman, TPI-MINN-93-55-T, UMN-TH-1227-93, TECHNION-PH-93-41, Nov. (1991) hep-ph/9311331; I. I. Bigi, UND-HEP-96-BIG06, Nov. (1996) hep-ph/9612293; B. Guberina and B. Melic, *Eur. Phys. J.* **C2**, 697 (1998).
13. E. M. Aitala *et al.*, *Phys. Rev. Lett.* **77** 2384 (1996).
14. R. Godang *et al.*, *Phys. Rev. Lett.* **84** 5038 (2000).
15. J. M. Link *et al.*, *Phys. Lett.* **B485** 62 (2000).
16. D. Cronin-Hennessy *et al.*, "Mixing and CP Violation in the Decay of Neutral D Mesons at CLEO", CLEO-CONF-01-1 Feb. (2001) hep-ex/0102006.
17. M. Grothe, *these proceedings*; and B. Aubert *et al.*, "Search for a Lifetime Difference in D^0 Decays", BABAR-CONF-01/29, SLAC-PUB-8983, Sep. (2001) hep-ex/0109008.

18. K. Abe *et al.*, “A Measurement of Lifetime Difference in D^0 Meson Decays”, KEK preprint 2001-143, BELLE preprint 2001-18, Nov. (2001) hep-ex/0111026.
19. J. M. Link, FOCUS Collaboration, “ $D^0 - \overline{D}^0$ Mixing in FOCUS”, Jun (2001). To appear in the proceedings of 36th Rencontres de Moriond on Electroweak Interactions and Unified Theories, Les Arcs, France, Mar. 10-17 (2001) hep-ex/0106093; and J. M. Link *et al.*, Phys. Rev. Lett. **86** 2955.
20. D. Kim, FOCUS collaboration, “Recent Results on CP Lifetime Differences of Neutral D Mesons”, presented at the Frontiers in Contemporary Physics - II, Mar. 5-10 (2001). http://web.hep.uiuc.edu/home/doriskim/talks/fcp01/kim_doris_tr.pdf